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Numerical modelling and comparison of the performance of diffuser-type solar chimneys for power generation ☆

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HIGHLIGHTS

- Performance of diffuser-type solar chimney (SC) systems for power generation was studied.
- Diffuser-type SCs had better performance than the SC with a cylindrical chimney.
- Fully divergent solar chimney was the best among the configurations examined.
- H_d/R_{in} and AR showed important influence on the performance of diffuser-type SCs.
- A variable diffuser outlet to control the operation of a SC system was proposed.

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ABSTRACT

Theoretically, making the chimney top larger than the chimney base can increase the driving potential of the Solar Chimney (SC) system. Based on this concept, the divergent chimney (DSC), the cylindrical chimney with a divergent outlet (DOSC) and the cylindrical chimney with a divergent inlet (DISC) are numerically examined in this study for revealing their aerodynamic features and the capability of power generation. The simulating outcomes indicate that the diffuser-type SCs generally have a better power generation performance than the cylindrical SC: the optimal output of the examined DSCs is ~13.5 times higher than that of cylindrical SC; the increase in the output from the DISCs ranges from 2 to 10 times while the optimal situation from the DOSCs is only ~5 times. The difference in the system performance is further found to be related to the chimney geometric parameters that have critical impacts on the expansion loss in the divergent flow channel. Based on the aerodynamic characteristics of the diffuser-type SCs, a new controlling approach for the SC is proposed with a variable diffuser outlet and an example is illustrated by using the DOSC. The example reveals that the SC with the controlling treatment had a stable output for 7 h during the daytime and its power output is 60% higher than the SC without any control.

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1. Introduction

Solar Chimney (SC, also known as solar updraft chimney) for power generation is proposed as an alternative renewable energy technology for the sustainable development of communities. The thermal updraft inside the chimney, as a joint outcome of the green-house effect in the solar collector and the stack effect in the chimney, can drive a wind turbine (or multiple turbines) locating at the base of the chimney for electricity generation, and then is released into the high altitude via the chimney top (as shown in Fig. 1). This process converts solar insolation into the mechanical energy of air stream and ultimately into electricity power without any pollutant emission.

The feasibility and operating principle of SC for power generation, also known as Solar Chimney Power Plant (SCPP), was examined by a 195 m-high pilot SCPP built in Spain [1,2]. Several small-scale prototypes were subsequently built for studying both the thermal- and areo- dynamic characteristics of SC system [3–8]. Theoretical analysis has been carried out for discussing the efficiency of SCs and the ambient or structural impact on the system performance [9–14]. Numerical simulation with CFD models have been used to reveal details of the heat transferring process and

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Nomenclature

D	thickness of heat source in ground, m
E_{ext}	external emissivity
g	gravitational acceleration, m/s^2
h_s	heat transfer coefficient at roof surface, W/m^2 K
H	height, m
$\dot{m}$	mass flow rate, kg/s
P_{out}	power output, kW
p	pressure, Pa
$\triangle p$	driving potential, Pa
Q	heat generation rate in the solid ground boundary, kW/m^3
R	radius, m
T	temperature, K
u	velocity in axis direction, m/s
$\dot{V}$	volume flow rate, m^3/s
v	velocity in radial direction, m/s

Greek letters

ρ	air density, kg/m^3
μ	kinematic viscosity coefficient, Pa s
η	efficiency
α	transmissivity of collector roof
β	volumetric coefficient of thermal expansion, 1/K; absorption of the ground

Subscripts

0	ambient atmosphere
b	chimney bottom
chim	chimney
coll	collector
d	divergent section
gauge	gauge pressure
in	start of divergent section
out	end of divergent section
s	soil layer
t	chimney top
tur	turbine

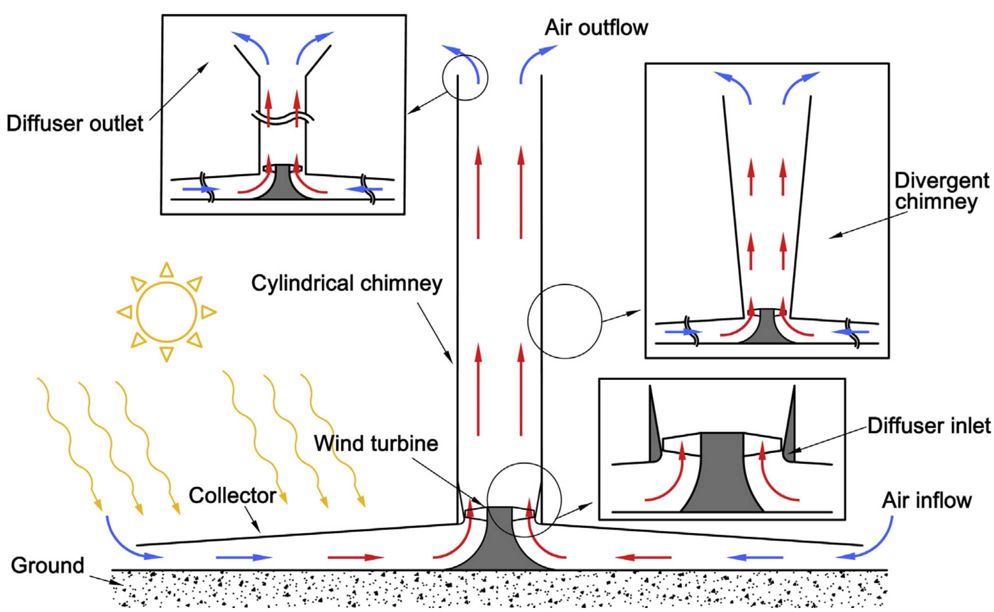

Fig. 1. Schematic diagram of the SCPP with different diffuser types adopted in previous studies.

the flow characteristics inside SCs and test novel structural designs for improving power output [15–19]. In recent years, SCs' operation has been extended to other fields, for instance, recovery of the low-grade waste heat from industrials [20–23], freshwater harvest with seawater distillation [24,25], grain drying [4] and energy storage coupled with fuel cells [26,27].

The driving potential for creating the air flow from the collector inlet to the chimney top can be expressed as (The derivation of the equation can be found in Appendix A)

$$\Delta P = (\rho_0 - \rho)gH_{chim} + \frac{1}{2}\rho v_b^2(1 - AR^{-2}) \tag{1}$$

where AR is the Area Ratio (AR) of the chimney top over the base. The equation above indicates that, if the chimney is cylindrical, the driving potential is equal to the air density difference between the SC inside and outside. It is consistent to the theoretical models established in previous studies [1,11]. On the other hand, when AR is over 1, a portion of dynamic pressure is converted into the static one, which contributes to the increase of the driving potential while the driving potential is diminished with ARs less than 1.

Chimneys with ARs higher than 1 have been examined in several studies. Koonsrisuk et al. [28] discussed how the flow area influences the power output of the Spanish prototype, and found that the divergent chimneys, whose cross section extended along the altitude (as shown in Fig. 1), significantly improved the performance of the SCPP. Patel et al. [29], Chergui et al. [30], Vieria et al. [31], Lebbi et al. [32] and Hu et al. [33] also reported that the divergent SCs could yield a power output of several times higher than the cylindrical SCs. Okada et al. [7] conducted a lab-scale experiment that compared a 2 m-high cylindrical chimney with a divergent one (with a divergent angle of 4°) and the latter chimney achieved a 3-time-faster updraft in the prototype. Coetzee et al.

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